Geomorphology 145–146 (2012) 115–122

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Comparison of slope instability screening tools following a large storm event and application to forest management and policy

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article info

Article history:
Received 14 June 2011
Received in revised form 31 December 2011
Accepted 4 January 2012
Available online 10 January 2012

Keywords:
Forestry
Landslide
Slope instability
Screening tools

abstract

The objective of this study was to assess and compare the ability of two slope instability screening tools developed by the Washington State Department of Natural Resources (WDNR) to assess landslide risks associated with forestry activities. HAZONE is based on a semi-quantitative method that incorporates the landslide frequency rate and landslide area rate for delivery of mapped landforms. SLPSTAB is a GIS-based model of inherent landform characteristics that utilizes slope geometry derived from DEMs and climatic data. Utilization of slope instability screening tools by geologists, land managers, and regulatory agencies can reduce the frequency and magnitude of landslides. Aquatic habitats are negatively impacted by elevated rates and magnitudes of landslides associated with forest management practices due to high sediment loads and alteration of stream channels and morphology. In 2007 a large storm with heavy rainfall impacted southwestern Washington State trigging over 2500 landslides. This storm event and accompanying landslides provides an opportunity to assess the slope stability screening tools developed by WDNR. Landslide density (up to 6.5 landslides per km^2) from the storm was highest in the areas designated by the screening tools as high hazard areas, and both of the screening tools were equal in their ability to predict landslide locations. Landslides that initiated in low hazard areas may have resulted from a varietyo fs ite-specific factors that deviated from assumed model values, from the inadequate identification of potentially unstable landforms due to low resolution DEMs, or from the inadequate implementation of the state Forest Practices Rules. We suggest that slope instability screening tools can be better utilized by forest management planners and regulators to meet policy goals regarding minimizing landslide rates and impacts to sensitive aquatic species.

1. Introduction

In the Pacific Northwest, landslide frequencies in areas with forest clearing are up to thirty-four times higher than natural background rates (Rood, 1984). Timber harvest is the primary factor responsible for this difference (Sidle et al., 1985). Landslides alter aquatic habitats by elevating sediment delivery, creating log jams, and causing debris flows that scour streams and stream valleys down to bedrock (Rood, 1984; Cederholm and Reid, 1987; Hogan et al., 1998). The short-term and long-term impacts of higher rates of landslides on fish include habitat loss, reduced access to spawning and rearing sites, loss of food resources, and direct mortality (Cederholm and Lestelle, 1974; Cederholm and Salo, 1979; Reeves et al., 1995). The restoration of geomorphic processes to natural disturbance regimes is crucial to the recovery of endangered salmonids (Oncorhynchus spp.) and other aquatic species in the Pacific Northwest as these species evolved under conditions with much lower sediment delivery and landslide frequency (Reeves et al., 1995; Montgomery, 2004).

In December 2007, a series of large storms moved through northwestern Oregon and southwestern Washington State. The storms brought heavy precipitation (up to 48 cm) and hurricane-force winds over four days (Mote et al., 2007). Significant flooding took place on numerous rivers in southwest Washington with record floods observed on the Chehalis River. Other rivers in the region recorded return period floods ranging from 2 to 100 years (Reiter, 2008). At least 2503 landslides were triggered in southwestern Washington by this storm event (Turner et al., 2010; Fig. 1). Upon entering steep and/or confined stream channels many of these landslides turned into debris avalanches, flows, and torrents (Sarikhan et al., 2008) further adding to the sediment volume of the original slides. Debris flows from landslides in smaller stream drainages can lead to short term stream discharge rates orders of magnitude above 100-year return period flood levels (Jakob and Jordan, 2001). Extrapolating from the number and area of the landslides, tens of millions of cubic meters of sediment, logs and debris were delivered to the stream networks in southwest Washington and northeast Oregon (Forest Debris Recovery Team, 2008; Sarikhan et al., 2008; ENTRIX,

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doi:10.1016/j.geomorph.2012.01.001

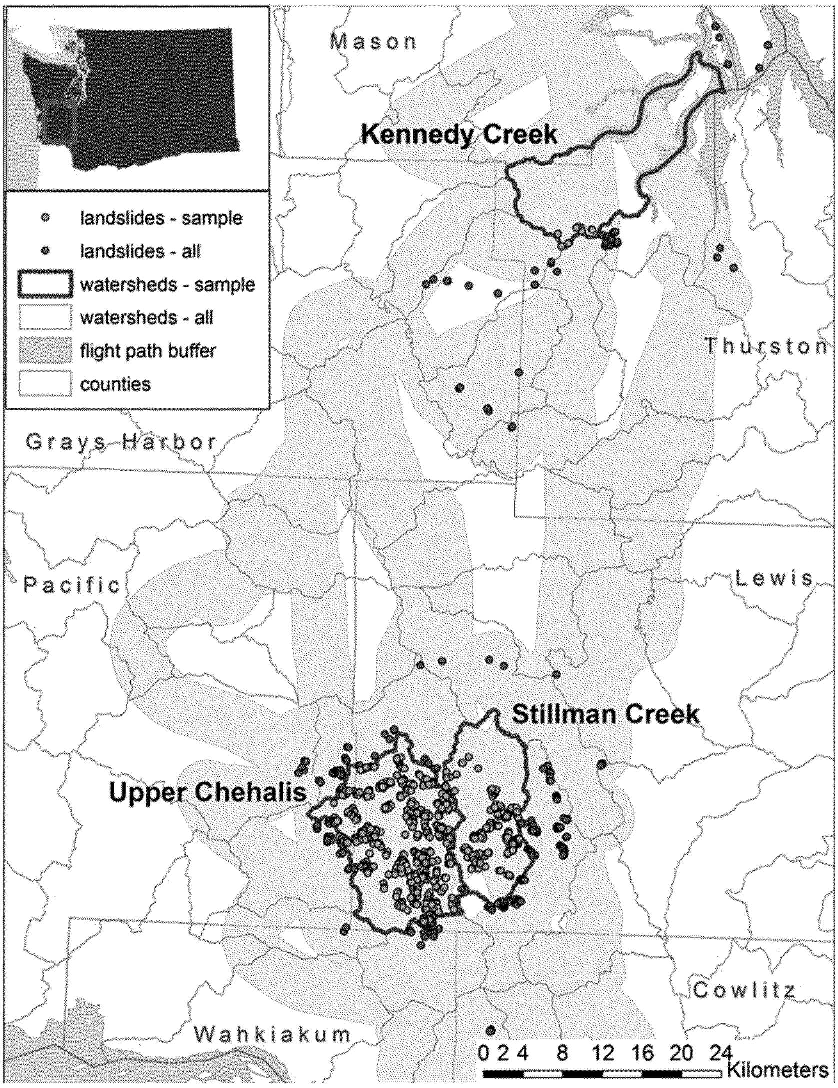


Fig. 1. Landslides from the December 2007 storm (WDNR, 2009) and watersheds sampled for this study (see Section 2.1).

2009). These streams were likely already aggraded from elevated sediment input rates associated with past forest practices (Stover and Montgomery, 2001).

Forest practices in Washington State are governed by state Forest Practices Rules which include site-specific prescriptions intended to prevent the increase in landsliding caused by forest practices beyond natural background rates in order to protect aquatic species and public resources (Washington Administrative Code (WAC) 222-10-030). For example, timber harvest, road-building, and related activities are limited on potentially unstable landforms (such as bedrock hollows, convergent headwalls, and inner gorges) on slopes steeper than 70% (35°; WAC 222-16-050(1)(d)). In response to the December 2007 storm, the effectiveness of the Forest Practices Rules at reducing landslide density and sediment delivery to the stream network was evaluated (Stewart et al., unpublished results). Where the Rules were fully implemented they appeared to be effective, but a large proportion (45%, N = 514) of the identified landslides that entered streams initiated at locations that had not been defined as potentially unstable by the Rules (the Rules did not apply to these sites; Stewart et al., unpublished results). Because the Rules were only partially effective in limiting landslide rates to background levels, improvements in the Forest Practices Rules for identifying potentially unstable landforms or improvements in their implementation may be needed.

Models have been developed as screening tools to identify locations of potentially unstable landforms. Use of these screening tools as hazard maps help forest managers determine where forest practices should or should not be located in order to minimize and avoid damage to aquatic habitats and other public resources as well as private property (Shaw and Vaugeois, 1999). The success with which slope instability screening tools can be applied in forest land management depends on evaluation of the accuracy of model predictions and the long-term response by land-use agencies (Wilcock et al., 2003). The objective of this study was to assess and compare the ability of two slope instability screening tools to predict actual landslide locations from the December 2007 storm. We show that these tools are useful in the identification of potentially unstable slopes, and we describe ways they can be better utilized in forest management to minimize landslide rates and harm to sensitive aquatic species.

2. Methods

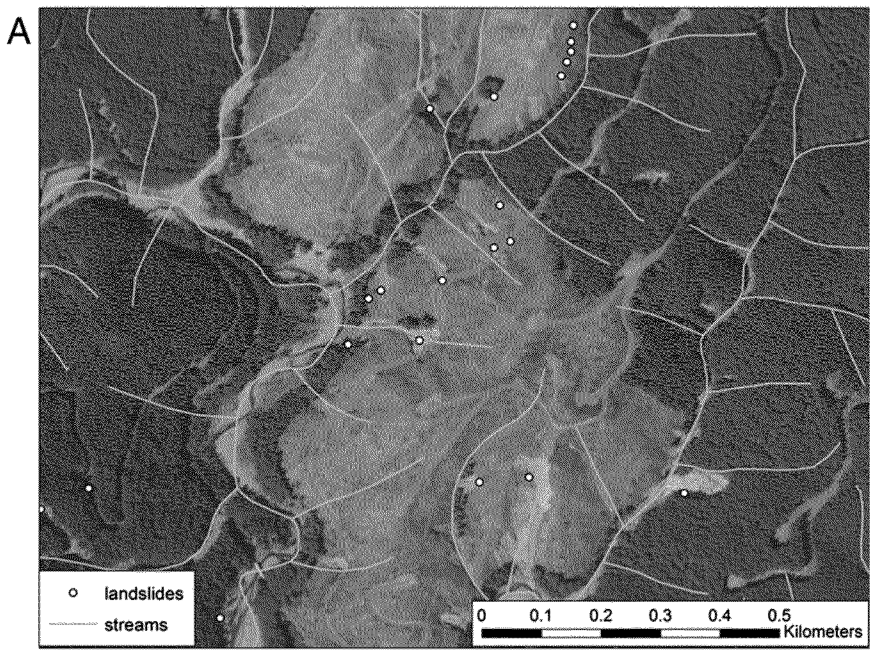
2.1. Study area and sample criteria

Landslide initiation point data was gathered by the Washington Department of Natural Resources (WDNR) during reconnaissance flights across southwest Washington immediately following the

December 2007 storm (WDNR, 2009; Fig. 2A). Each identified landslide from the December 2007 storm had to fit three criteria before we included it in our sample and determined the hazard rating (very high, high, medium, or low) predicted by each slope instability screening tool (Section 2.3; Table 1). First, only watersheds for which both slope instability screens could be applied were considered: Kennedy Creek (N = 11 landslides), Stillman Creek (N = 215 landslides), and the Chehalis Headwaters (N = 553 landslides; Fig. 1). All Kennedy Creek landslides occurred on WDNR-managed land, and 99% of Stillman Creek and Chehalis Headwaters landslides occurred on Weyerhaeuser Co. land (a private timber company). Second, only areas within 2743 m (9000 ft.) of the WDNR landslide reconnaissance flight paths were considered (Sarikhan et al., 2008; Fig. 1). This distance represents the extent visible on photos taken during the flights given the light conditions and topography (I. Sarikhan, WDNR, personal communication, 2009). Finally, only those land cover classes characteristic of working forestlands, where these screening tools are applied, were included in the study area (deciduous, evergreen, and mixed forest, barren land, shrub/scrub, herbaceous, woody wetlands, and developed open space; Homer et al., 2004).

2.2. Geological context

The Kennedy Creek watershed is located at the southwest edge of the Puget Lowlands province. Mapping by Logan and Walsh (2004) and WDNR (1995) indicate the watershed is underlain by glacial related sediments and Eocene basalts of the Crescent Formation. The Puget ice lobe extended into and over all but the southernmost area of the watershed area during the pre-late Wisconsinan glacial period. Glacial ice reached only the lower northern end of the watershed



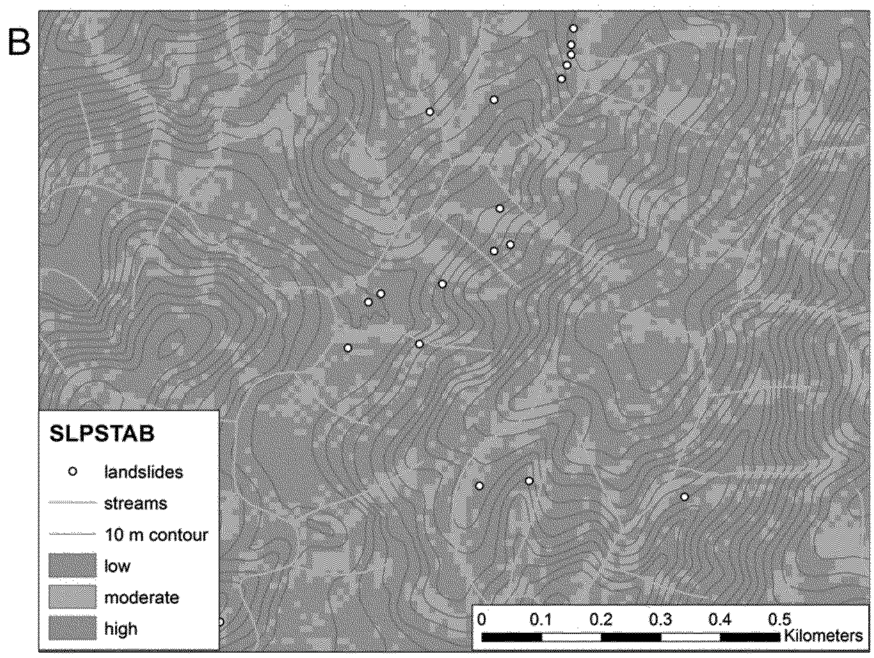


Fig. 2. Landslide initiation points relative to (A) forest and road cover and slope instability categories defined by (B) SLPSTAB and (C) HAZONE.

C

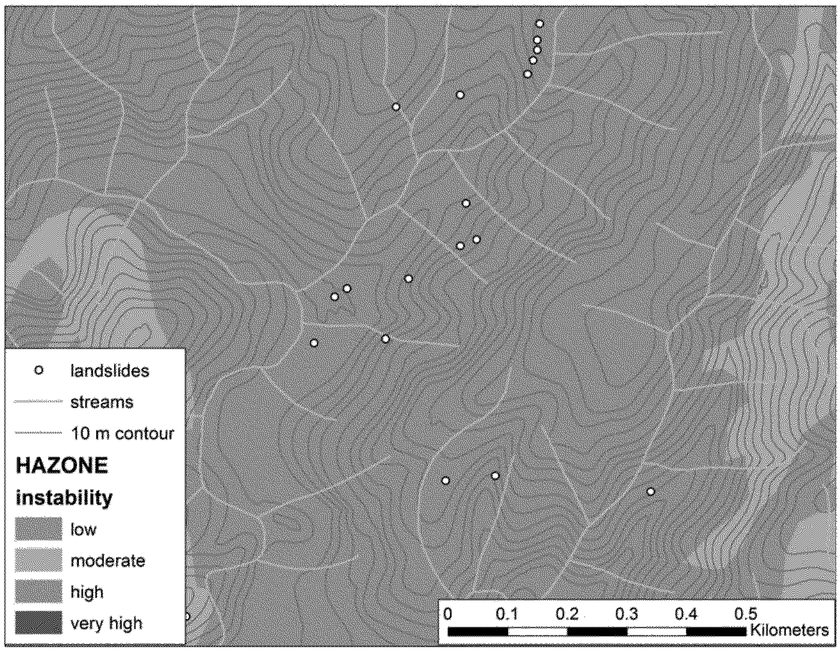


Fig. 2 (continued).

during the last glacial period approximately 18,000 years BP. Bedrock was eroded and glacial related sediments were deposited on lower valley slopes with very thin glacial till to no glacial deposits on upper and steeper slopes. The Kennedy Creek valley served as a glacial melt water outlet draining the southwest margin of the ice lobe to valleys to the southwest. Since the ice has retreated the streams in the northern portion of the watershed have been down-cutting through the thicker glacial sediments. The southern edge of the watershed includes the north slope of the Black Hills. The glacial ice did not cover these slopes, and the slopes in this area are sharper consisting of steep sided ridges separated by steep incised stream channels.

The Stillman Creek and Chehalis Headwaters watersheds are neighboring headwater basins of the Chehalis River located in the Willapa Hills province. This area has not been glaciated. The higher elevation portions of the watersheds are underlain by lower to middle Eocene Crescent Formation, Eocene intrusive rocks, and Eocene tuffs, and the lower portions of the watershed are underlain by Eocene marine sedimentary rocks (Walsh et al., 1987). The Crescent Formation is predominantly composed of fine grained submarine basalt flows with localized thin interbeds of tuff and siltstone. The intrusive rocks consist of gabbro, diabase, and basalt dikes and sills. The tuffs are mafic to silicic and are submarine. The lower reaches of both watersheds are predominantly marine sedimentary rocks ranging from laminated to massive siltstone and claystone to crossbedded sandstones with lesser interbeds of tuff and basalt flows, breccias, and conglomerates. The Stillman Creek and Chehalis Headwaters watersheds are characterized as highly incised steep sided ridges and valleys with elevation difference between the larger stream valley bottoms and ridges on the order of 2000 ft and average slopes greater than 30° with much steeper slopes in convergent or deeply eroded areas. Due to lack of glaciation, depth of bedrock weathering varies based on slope aspects and bedrock types with marine sedimentary units generally more deeply weathered (Sarikhan et al., 2008).

Table 1
Number of landslides per watershed by slope instability screening tool and hazard category (not normalized by area). None of the areas in the Kennedy Creek or Stillman Creek watersheds were classified as very high hazard by the HAZONE model. Landslides in the low hazard category were considered incorrect (Type I errors).

	HAZONE				SLPSTAB		
Watershed	Low	Moderate	High	Very high	Low	Moderate	High
Kennedy Creek	7	1	3	NA	5	5	1
Stillman Creek	105	98	12	NA	114	63	38
Chehalis Headwaters	73	284	189	7	199	189	165
Total	185	383	204	7	318	257	204

2.3. Slope instability screening tools

In Washington State, two slope instability screening tools have been developed for use in forest practice planning and permitting by the WDNR, the agency charged with forest practice regulation and management of state forest trust lands: SLPSTAB (Vaugeois, 2000) and HAZONE (WDNR, 2010). The screening tools are used by WDNR during the forest practices application process to flag potentially unstable slopes where timber harvest, road building, or related activities are being proposed. SLPSTAB is a GIS-based screening tool of inherent landform characteristics that covers all or most of 488 watersheds of western Washington (Vaugeois, 2000; Fig. 2B). It was derived from two deterministic, physically-based models — SMORPH (Shaw and Johnson, 1995) and SHALSTAB (Montgomery and Dietrich, 1994) — that assume that topographic relief (i.e., hillslope gradient) and form (i.e., slope curvature) are the principal driving factors in promoting shallow landslides (Vaugeois and Shaw, 2000). SLPSTAB utilizes slope geometry derived from 10-m digital elevation models (DEMs) and climatic data establishing frequency of critical rainfall (Q_c per Montgomery et al., 1998) in a given area that would cause a slope to become unstable. SLPSTAB categorizes the risk of shallow-rapid landslide potential as low, medium, or high based on a semi-quantitative matrix approach that uses two-year, 24-hour storm isohyte data to create precipitation rules for each test basin (Vaugeois and Shaw, 2000). The screening tool has been calibrated to specific areas with landslide inventories, soils, mass wasting units, geology, and precipitation data. SLPSTAB model output is viewable to the public through the Forest Practices Application Review System resource maps online (WDNR, 2007), or its GIS raster file can be downloaded (WDNR, 2010).

HAZONE, on the other hand, is a screening tool developed using a more inferential approach. The predictive capability of HAZONE relies on the past as prediction for hazard potential, an approach consistent with standard geomorphic analysis of an area. HAZONE hazard ratings are based on a semi-quantitative assessment method that incorporates slope stability data from previously existing watershed analyses; public, tribal, and private assessments; and the State Landslide Hazard Zonation project (UPSAG, 2006). This screening tool was derived from aerial photos; topographic, geologic, and hydrologic maps; 10 m or LiDAR (Light Detection and Ranging) DEM; and field observations; and it covers all or most of 142 watersheds (WDNR, 2010; Fig. 2C). A key variable in establishing hazard zones in the HAZONE screening tool is historic landslide density normalized over time, or more specifically, the landslide frequency rate and landslide area rate for delivery of a given landform (UPSAG, 2006). Low hazard areas have no historic landslides or any other attributes of slope instability and include landforms such as valley bottoms, terrace surfaces, or low gradient hillsides. Moderate hazard areas include landforms that occasionally generate landslides (such as the bodies of deep-seated landslides) and have some documented sensitivity to forest practices (such as steep planar slopes with road drainage-related failures). Toes and headscarps of active deep-seated landslides or steep and potentially unstable landforms that meet specific regulatory criteria (WAC 222-16-050) receive a high or very high hazard rating (UPSAG, 2006). HAZONE can be downloaded as a GIS vector file (WDNR, 2010).

2.4. Statistical analysis

To assess the predictive abilities of the two screening tools for this storm event, we calculated landslide densities (landslides/km ^{2}) within each hazard zone for each tool and type I error rates for each tool and watershed. To detect differences in landslide density between hazard zones, we conducted a χ^2 test for each screening tool, assuming expected values to be in proportion to the area in each hazard zone (Montgomery et al., 1998). To assess differences in the area encompassed by each hazard zone, we conducted another χ^2 test for each screening tool, assuming expected values to be equal between hazard zones. To compare the relative predictive abilities of the two screening tools, we conducted a Wilcoxon Signed Rank test (a non-parametric test for non-normally distributed, small, independent samples), which tests the null hypothesis that the distributions of the two groups are equal. For this test, type I error rates were defined as the ratio of incorrectly predicted landslides (those that initiated at sites outside of areas defined by the screening tools as unstable, i.e., in low hazard areas) to the total landslides per watershed (Shaw and Vaugeois, 1999). We conducted all tests using the statistical software SPSS 13.0 (Chicago, IL, USA) and set α at $p=0.05$ (2-tailed).

3. Results

Landslide density (landslides/km ^{2}) was significantly higher in areas designated by both models as high hazard areas. For the HAZONE tool, landslide density ranged from 0.9 landslides/km ^{2} in the low hazard category to 6.5 landslides/km ^{2} in the very high hazard category ($\chi^2=751$, df=3, pb0.0001; Fig. 3). For the SLPSTAB tool, landslide density ranged from 1.4 landslides/km ^{2} in the low hazard category to 5.5 landslides/km ^{2} in the very high hazard category SLPSTAB: $\chi^2=23$, df=2, pb0.0001; Fig. 3).

Landslides did not occur in direct proportion to the area mapped in each hazard category (Fig. 4). For the HAZONE tool, 27% of the landslides occurred in high and very high hazard areas, which represent only 11.9% of the total area (42.7 km ^{2}). When moderate hazard areas are added to this, 76.3% of the landslides were included and 39.8% of the total area (km ^{2}) was covered. Differences in the areas of hazard zones mapped by HAZONE were significant ($\chi^2=292$, df=3, pb0.0001). For the SLPSTAB tool, 26% of the landslides occurred in

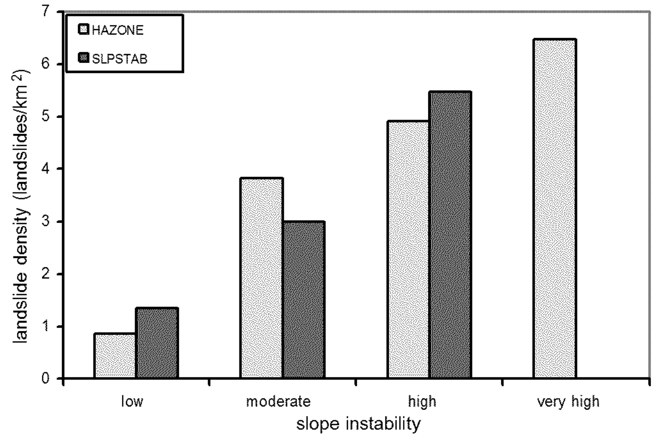


Fig. 3. Landslide density (landslides/km^2) by slope instability category and model. The SLPSTAB model does not include a very high hazard category.

high hazard areas, which represent only 10.4% of the total area (37.2 km ^{2}). When moderate hazard areas are added to this, 59.2% of the landslides were included and 34.2% of the total area (km ^{2}) was covered. Differences in the areas of hazard zones mapped by SLPSTAB were also significant ($\chi^2=180$, df=2, pb0.0001). Thus the screening tool hazard categories were useful for predicting where the highest and lowest concentrations of landslides would occur.

Neither slope instability screening tool showed a superior predictive ability over the other. The mean number of landslides that took place in areas designated as low hazard areas (type I errors) per watershed was similar between the two tools tested (42% for HAZONE and 45% for SLPSTAB; Table 2). The Wilcoxon rank sum test showed the distributions of this subset of landslides did not differ statistically between tools (Wilcoxon W = 10.0, p = 0.827). When all three watersheds were combined, the type I error rate was lower: 24% for HAZONE and 41% for SLPSTAB (Table 2). SLPSTAB had more slides in low hazard areas than HAZONE overall, whereas HAZONE had greater variance in the number of slides that took place in low hazard areas per watershed than SLPSTAB.

4. Discussion

The hazard categories mapped by both slope instability screening tools were useful for predicting sites more likely to have slope failures from this storm event within the three watersheds examined. Zones predicted to have the highest landslide hazard showed the highest landslide density and the smallest area among hazard categories.

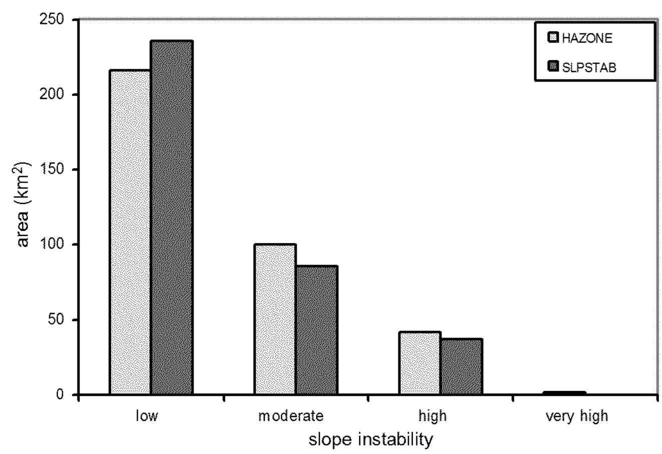


Fig. 4. Area (km^2) in each slope instability category by model. The SLPSTAB model does not include a very high hazard category.

Table 2
Ratio of incorrect landslides (in low hazard areas) to total landslides per watershed (Type I error rates, Wilcoxon rank sum test input).

		HAZONE		SLPSTAB	
Watershed	Total landslides	Incorrect landslides	Incorrect/total landslides	Incorrect landslides	Incorrect/total landslides
Chehalis Headwaters	553	73	0.13	199	0.36
Kennedy Creek	11	7	0.64	5	0.45
Stillman Creek	215	105	0.49	114	0.53
Mean	259.7	61.7	0.42	106.0	0.45
SD	273.7	50.0	0.26	97.2	0.09
Total	779	185	0.24	318	0.41

Landslide density was lowest in areas predicted to have the lowest landslide hazard, which comprised the largest area. Our results indicate that both HAZONE and SLPSTAB are effective methods for recognizing potentially unstable slopes.

Other studies have found similar results. A test of SHALSTAB (Montgomery and Dietrich, 1994; from which SLPSTAB was partially derived) showed areas predicted to have lower critical steady-state rainfall (Q_c) necessary to trigger slope instability (i.e., high hazard areas) consistently had higher landslide densities both within each watershed and across all watersheds examined (Montgomery et al., 1998). As assessment of SHALSTAB and SMORPH also found landslide densities increased with hazard class for both models (Pacific Watershed Associates, 2008). Landslide density may not be the best proxy for aquatic habitat disturbance due to variability in the volume of sediment and debris delivered to a stream with landslide gradient and size (Brardinoni et al., 2009). A better dependent variable for measuring impacts to aquatic habitats would be the volume of sediment and debris delivered to streams, but unfortunately these data were not available for this study.

Others have also found the highest hazard zones to occupy the least area across watersheds. A regional analysis of 14 watersheds in Washington and Oregon found only 13% of the total area was classified as high hazard, which represents a small and topographically identifiable portion of the region (Montgomery et al., 1998). A study of two watersheds in northern California mapped 4% of the area and 58% of landslides in high hazard zones (Pacific Watershed Associates, 2008). A similar relationship was found in Oregon, where sites with the highest probabilities of initiating or transporting debris flows made up a relatively small percentage of the study area (Burnett and Miller, 2007). This pattern has important implications for forest management and policy making strategies that aim to concentrate land use restrictions over the smallest area possible to minimize economic impacts to landowners while effectively minimizing landslide rates.

Landslides occurred in areas that both models designated as low hazard areas, but the rate of these slides (type I errors) was similar for both screening tools tested. Statistically, neither tool showed a greater ability to predict landslide locations than the other. In a similar comparison of slope instability screening tools that were precursors to the SLPSTAB model Shaw and Vaugeois (1999) found no significant difference in type I error rates between the SMORPH and SHALSTAB models and hazard zonation maps later utilized by the HAZONE screening tool. We observed fewer slides in low hazard areas for HAZONE than SLPSTAB overall (24% and 41% respectively). Overall type I error rates reported by Shaw and Vaugeois (1999) were lower (3% for SMORPH and 8% for SHALSTAB). A test of SHALSTAB (Montgomery et al., 1998) reported a 24% type I error rate across 14 watersheds and highly variable error rates between watersheds that ranged from 6% to 88%. In a different assessment, landslides were incorrectly predicted by SHALSTAB in 25% of cases and by SMORPH in only 0.5% of cases (Pacific Watershed Associates, 2008).

The overall type I error rates we observed probably would have been lower if we had utilized different methods for mapping landslides (polygons instead of initiation points), less stringent methods for classifying type I errors (assigned each landslide with the highest hazard of all pixels within the polygon), and a larger sample of landslide and rainfall events spatially and temporally (more than three watersheds and one storm), as other studies have done (Montgomery et al., 1998; Shaw and Vaugeois, 1999; Pacific Watershed Associates 2008). Under the strict classification criterion used for this study (hazard level of a single 10 m^2 pixel or variable-sized polygon in which a landslide initiation point occurred), we consider the percent of correctly predicted landslides (59–76% for SLPSTAB and HAZONE, respectively) to indicate these two screening tools are good predictors of landslide hazard. The difference in overall type I error rates between these two tools may have been related to the difference in the tools' resolutions, with a higher error rate for SLPSTAB's 10 m^2 pixel (Fig. 2B) than for HAZONE's variable-sized polygons (Fig. 2C). Small mapping errors in a landslide initiation points are more likely to lead to classification errors on higher resolution maps if classification is based on the hazard level of a single pixel.

Many of the errors reported by Montgomery et al. (1998) occurred because the DEM utilized in the models did not detect all landform locations subject to slope failures (at finer resolution than a 30-m DEM), but these smaller landforms were readily detectable in the field. The SLPSTAB tool assessed in this study was run with a finer 10-m DEM, but even with this finer topographic resolution unstable slope landforms will still be missed and will still contribute to type I errors. Hence low DEM resolution can be a significant source of type I errors in areas that were designated as low hazard areas (Brardinoni et al., 2003). SLPSTAB tool performance could improve with the use of higher resolution digital elevation data such as LiDAR (Dietrich and Montgomery, 1998; Shaw and Vaugeois, 1999). Another factor is the variability of rain fall events as well as variability of rain fall across geographic areas from a single storm event. SLPSTAB hazard designations are in part established based on a return frequency of critical rainfall threshold events. For the 2007 storm, the rainfall intensity was very high and caused slope instability on a wider range of slopes than would have taken place during a less intense storm. The SLPSTAB screening tool would benefit from better refined climatic models that would better predict frequency of critical rainfall thresholds. Type I errors are also more likely for SLPSTAB at sites where soil parameters such as cohesion and internal angle of friction deviate from assumed default values due to local lithology or where geologic structures are stronger influences than topographic landform alone on slope instability (Montgomery et al., 1998). Sarikhan and others (2008) noted greater landslide density within Crescent Formation units versus other units within the Stillman Creek and Chehalis Headwaters watersheds during the storm event. There are a number of possible explanations for this discrepancy. The areas underlain by Crescent Formation tend to be in the higher and steeper portions of the watersheds, and higher elevation coincides with higher precipitation. These factors should be reflected within the screening tools. However, the Crescent Formation basalts are more resistant to deep weathering than the more marine sedimentary units. The Crescent Formation subsurface stability parameters will differ from the more deeply weathered marine sedimentary units in a manner that may lead to the marine sedimentary units being more stable than topography alone would otherwise indicate. Hence, actual subsurface conditions that differ from those assumed or simulated in the screening tools can result in higher or lower potential slope instability. In particular, high pore water pressures can exist for reasons other than topographic convergence and cause landslides to occur on planar and gentle slopes. For example, minor drainage alteration along both new and legacy logging roads or along skidder routes can concentrate subsurface pore water. In areas of deeply weathered bedrock, residuum soils with lower porosity can concentrate subsurface water in an unpredictable manner.

The number of slides reported here both within areas the screening tools indicated as low hazard areas (type I error rates) or within high hazard areas should be treated as estimates rather than absolute values. The number of landslides detected by aerial surveys can be affected by the presence of forest canopy or narrow channels (Robison et al., 1999; Brardinoni et al., 2003; Miller and Burnett, 2007; Turner et al., 2010). A test of this relationship was not conducted due to the limits of landslide inventory data available to the public (WDNR, 2009).

5. Management and policy implications

Assessing potential landslide risk is an important component of forest management. Besides the impacts to forest soils and the forest itself, landslides can impact down slope properties, stream and river systems, and other public resources, with an increased rate of delivery of sediment from landslides taking place at a greater frequency and magnitude than under natural background conditions (Rood, 1984; Montgomery et al., 2000). These impacts are common among managed forest watersheds of the Pacific Northwest, and have contributed to the habitat degradation and decline of endangered salmonid, amphibian, and other native aquatic species that are unable to adapt to the altered disturbance regime (Cederholm and Lestelle, 1974; Welsh and Ollivier, 1998; Montgomery, 2004). The long-term survival of many endangered fish stocks will depend on a new management paradigm that emphasizes the restoration of basic habitat integrity and ecosystem processes, including landslide rates closer to natural background levels, while incorporating the needs of other native aquatic species (Nehlsen et al., 1991; Reeves et al., 1995; Montgomery, 2004).

Forestry presents a challenge for landslide hazard assessment, but many of the most valuable forest areas in the world are located within temperate mountain belts (NASA, 2011) with steep terrain that can be susceptible to landsliding. In forested mountainous terrain knowledge of geologic and soil parameters are general in nature, and detailed features of the terrain can be difficult to ascertain due to thick forest cover. This last aspect may be greatly alleviated with the greater coverage of areas by ground surface LiDAR and the trend toward even more accurate GIS-based DEMs. Forest practice planning and review has been evolving in Washington State due to the recognition that increased rates and magnitudes of landslides due to timber management activities have impacted aquatic resources. In Washington State, if forest practices are proposed on potentially unstable landforms that meet specific criteria, further evaluation for impacts to the environment must be conducted through the State Environmental Policy Act (SEPA; WAC 222-16-050(1)(d)). This requirement can be avoided by excluding these landforms from harvest units, but in forested mountainous or hilly terrain identifying potentially unstable areas poses a challenge to foresters charged with ensuring that forest practices do not cause significant harm to the environment. Hence, the HAZONE and SLPSTAB screening tools were developed to assist both foresters and regulators in identifying and avoiding unstable slopes.

The December 2007 storm provides an opportunity to not only evaluate the two screening tools used in Washington State but also an opportunity to identify potential problems in the forest practice rules and their implementation regarding unstable slopes. During the December 2007 storm, 45% (N = 514) of landslides that entered streams initiated at locations that had not been identified as potentially unstable during the forest practices review process, and the majority of those slides took place in areas that had been relatively recently harvested (Stewart et al. unpublished results and our own observations). This may have resulted from the inadequate identification of potentially unstable landforms or the inadequate implementation of the state Forest Practices Rules.

The two slope instability screening tools assessed here indicate that slope stability screening tools work well for identifying potentially unstable slopes. However, these screening tools are not currently formally used during the forest practice review process in Washington State. Even though the HAZONE and SLPSTAB screening tools indicated the presence of potentially unstable slopes, forest practices took place within these areas because they were not formally designated as high hazard areas.

The forest practice review process begins with a screening by WDNR staff for the presence of unstable slopes in the proposed harvest unit(s) according to a soils map, SLPSTAB, and HAZONE. By default, no SEPA review of applications is required regardless of the screening tool map output (WDNR, personal communication, 2010). For a forest practice to be subject to SEPA review, the proposed activity must also be "field verified by the department" (WAC 222-16-050(1)(d)). Workload constraints and the large areas covered by forest practice proposals prevent field visits to all of the sites where field review is needed (WDNR, personal communication, 2010). Because of this, forest practices can take place on slopes that were identified by the screening tools as high landslide hazard areas without any further regulatory review. We suggest that statistically both the HAZONE and SLPSTAB screening tools are an effective means of identifying potentially unstable slopes and that all forest practices that take place within such areas be subject to field verification as to whether or not an area meets the specific criteria of an unstable landform. Implementing this change to the forest practice review process ought to lead to better identification and protection of potentially unstable slopes and aquatic habitats.

6. Conclusions

During the December 2007 storm in southwest Washington, the highest landslide density occurred where slope instability screening tools indicated the highest risk of hazard, and the tools were equal in their ability to predict landslide locations. Many landslides initiated on sites identified by the screening tools as unstable, but that had not been identified as unstable though the forest practices review process. We suggest that the slope instability screening tools we reviewed can be better utilized by forest management planners and regulators to meet policy goals regarding minimizing landslide rates and impacts to sensitive aquatic species. This type of adaptive management will become increasingly important as the Pacific Northwest experiences more frequent and intense storms predicted by climate change models (Dale et al., 2001; Christensen et al., 2007; Karl et al., 2009).

Acknowledgements

WDNR staff provided landslide GIS data, background information on the screening tools, and useful insights into the forest practice review process. StatCom at the University of Washington provided statistical consulting. Constructive comments on this manuscript were provided by two anonymous reviewers.

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